APPLICATION OF DIGITAL-COMPUTER TECHNIQUES TO

THE STUDY OF THE IMPACT DYNAMICS OF

LUNAR-LANDING VEHICLES

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APPLICATION OF DIGITAL-COMPUTER TECHNIQUES TO THE STUDY OF THE IMPACT DYNAMICS OF LUNAR-LANDING VEHICLES

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ABSTRACT

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The Langley Research Center is currently conducting a combined analytical and experimental study of the dynamics of lunar-landing vehicles. This paper deals with the analytical phase of this work. It outlines the general mathematical model and the idealizations of the structure and landing surface employed to simplify derivation of the equations of motion in three-dimensional space. Special attention is given to idealization of shock absorbers and the interactions between footpads and the surface. A digital-computer program for solution of the equations of motion is discussed. Computed motion time histories are presented which show shock absorber action and vehicle accelerations for a realistic lunar-landing vehicle during the landing process from touchdown to rest.

author

INTRODUCTION

The landing gear for a spacecraft for manned lunar landing is required to arrest the descent, under lunar gravity, of a vehicle with earth weight upwards of 11,000 pounds impacting at velocities up to 10 feet per second vertical and 5 feet per second horizontal. In the process, the gear must prevent impact damage and bring the craft to rest in an attitude which will not inhibit re-launch.

There is uncertainty about the character of the lunar surface, the degree of choice which the pilot can exercise in selecting a landing site, and the extent to which the pilot can control velocity and orientation relative to the surface at impact.

At present it is generally accepted that the gear should be some system of legs built of thin-walled tubular struts, the struts containing load-limiting shock absorbers. One conception is illustrated in figure 1.

Figure 1 is a photograph of a mock-up of an early proposal for the Apollo Lunar Excursion Module, the vehicle which will ferry astronauts from lunar orbit down to the surface of the moon and subsequently launch them back into lunar orbit. The mock-up represents a four-legged vehicle, but only two legs are mounted. The bulbous objects mounted in the leg struts are shock absorbers. Different leg designs have evolved since this mock-up was created, but the preference for a vehicle with legs as opposed to, say, a landing gear fashioned from a gas-filled bag has been maintained.

Organizations undertaking research, design, or system evaluation with regard to the landing gear have found it necessary to investigate the effectiveness of such leg systems considering a wide range of combinations of impact velocity and orientation and considering very general conditions of topography and constituency of the landing site.

The mechanical operations of this sort of gear are generally so closely coupled with motions of the vehicle, during an impact, that no satisfactory way has been found to investigate a leg as a subsystem apart from the vehicle system. Both in laboratory tests and in theoretical analysis of the functioning of a gear, it seems necessary to consider the dynamics of the entire vehicle.

In testing on earth there is considerable difficulty in simulating even what is known of the lunar environment. Of particular significance as regards landing tests is the fact that it is very difficult at best to devise a lunar gravity simulator which will work during an impact. Therefore, heavy reliance is being placed on theory, theory thoroughly checked out by the kind of tests which can be conducted on earth, for descriptions of vehicle behavior under actual lunar conditions. Currently, there are several groups working vigorously along the following lines: Vehicle equations of motion are derived, and a digital computer program is devised for generating numerical solutions of the equations. A dynamic model is constructed, incorporating as many of the mechanical actions of an actual vehicle as is feasible. The dynamic behavior of the model during impacts under earth gravity is observed and measured, and motion histories obtained by theory and by experiment are compared in detail. The correlation is studied, and the theory is refined. Most of the feel that has developed around the country concerning the impact behavior of a lunar-landing vehicle has been acquired in this manner, and there is little doubt that significant design and system evaluation decisions affecting the initial landing will rest on the dynamical histories ground out by these computer programs.

The Langley Research Center is conducting parallel analytical and experimental programs aimed at contributing to this general effort to arrive at a broad understanding of lunar landing dynamics. This paper deals with this work. It was originally intended to cover only analytical procedures. But shortly before the oral presentation it became possible to make a couple of interesting comparisons of experiment and theory, and some discussion is devoted to these.

ANALYTICAL MODEL

Figure 2 illustrates the analytical representation we are using for a lunar-landing vehicle. The vehicle is treated as an arbitrary rigid body to which there are attached legs, each leg consisting of three struts in an inverted tripod arrangement. There may be three or four legs. The struts are connected to the body by universal joints, and the apex point of a tripod, which we call a foot, is also a universal joint. There is a shock absorber in each strut. The individual struts may shorten or lengthen due to stroking of the shock absorbers but are otherwise nondeformable. The locations of the points on the body where the struts attach, and the initial positions of the feet relative to the body may be arbitrarily chosen. The legs are considered to have no mass. In representing an actual vehicle or model the masses and moments of inertia of the legs and footpads are lumped in with the body mass and moment of inertia.

The assumption that the leg inertias may be pushed into the body permits considerable simplification of the equations of motion, eliminating several degrees of freedom and eliminating problems in numerical integration connected with inertial coupling in the equations. It is rather generally felt that the approximation involved is tolerable, but this has not as yet been rigorously determined.

The assumption of inverted tripod legs, though appropriate for our own dynamic model, has proved restrictive for general applications. However, reprograming to allow more general strut arrangements is simple.

SHOCK ABSORBERS

The shock absorber in a strut, when stroking, is considered to produce a force acting along the instantaneous axis of the strut. The magnitude of this force is considered to be a function of stroking rate only. The form assumed for this function is shown in figure 3.

The subscript j denotes a particular leg, and the subscript i is used to identify a given strut in that leg. The horizontal axis V is stroking rate. Positive values of V indicate that the strut is shortening; negative values indicate lengthening. The vertical axis is the absolute value of the stroke load F, the axial force resisting shortening. The stroke load is taken to be a ramp function of the stroking rate V. For example, if a strut is closing the stroke load is proportional to the closing rate up to a certain value of closing rate denoted VC. For values of the closing rate greater than VC the stroke load remains constant at a value denoted by FC. Both FC and VC and the corresponding values for an opening strut, FO and VO, may be arbitrarily assigned. In particular, VC can be set equal to zero, giving constant force stroking as could be obtained with a crushable aluminum honeycomb shock absorber, or VC can be set at a very high value, giving effectively a stroke load proportional to stroking rate as would be obtained with a viscous damper.

LANDING SURFACE

Figure 4 illustrates the analytical model of the landing surface. The boundary of the landing surface is represented by a set of arbitrarily oriented planes, one plane associated with each foot. Use of a different plane for each foot allows us to get the effect of an irregular surface. When the jth foot is above its associated landing surface plane, the entire jth leg is assumed to move with the body as though the leg were a rigid extension of the body. When the jth foot is beneath its associated plane but has a normal component of velocity carrying it toward the surface of the plane, that is, if the foot is emerging from beneath the surface, then also we consider the leg to move as a rigid extension of the body, giving the effect of an unimpeded lift-off of a foot. When the jth foot is beneath its associated plane, and is penetrating, the following rule is used for computing the velocity vector of the foot:

Associated with the jth landing surface plane, there are assigned two coefficients of viscous friction, one for friction resisting motion of the foot normal to the plane, the other for friction resisting motion of the foot tangential to the plane. When the jth foot is penetrating, the normal and tangential components of velocity of the foot are determined by requiring that the resultant instantaneous friction force on the foot exactly balance the instantaneous resultant force produced by the three shock absorbers bearing on the foot. Thus, in the analysis a penetrating foot moves in the manner of a very light mass being pushed through a viscous medium by the shock absorber forces.

EQUATIONS OF MOTION

The rules discussed in the previous section govern the motion of the feet. The equations following are the equations of motion of the rigid body to which the struts are attached.

$$M\ddot{X} = F_X$$

$$M\ddot{Y} = F_Y$$

$$M\ddot{Z} = F_Z$$

$$I_\xi \dot{\omega}_\xi + \left(I_\zeta - I_\eta\right)\omega_\eta \omega_\zeta = N_\xi$$

$$I_\eta \dot{\omega}_\eta + \left(I_\xi - I_\zeta\right)\omega_\zeta \omega_\xi = N_\eta$$

$$I_\zeta \dot{\omega}_\zeta + \left(I_\eta - I_\xi\right)\omega_\xi \omega_\eta = N_\zeta$$

The first three equations are the elementary translation equations for the body center of gravity referred to a set of inertial axes (X,Y,Z) which are fixed with respect to the landing surface. M is the total mass, and the F's are the components of the shock absorber and gravitational forces acting on the body. A dot indicates differentiation with respect to time.

The remaining three equations are the classic Euler equations. The ω's are components of angular velocity referred to principal axes (ξ,η,ζ) fixed in the body. The I's are the principal moments of inertia associated with the body axes. The N's are the resultant torques about the body axes produced by the action of the shock absorber forces.

These are six-degree-of-freedom equations and impose no restrictions on motions of the body. It is emphasized that the frequently used assumption of symmetrical impact in which the vehicle executes only two-dimensional tumbling motions is not employed in this analysis. The vehicle may strike and tumble with the most general of motions. Earlier work, which we reported (ref. 1), established that equations allowing three-dimensional motion are indeed required, since the most critical cases as regards the stability of a vehicle against overturning can be connected with asymmetrical impacts.

Once integrals of these equations have been computed one may, with the use of well-known transformations, compute the velocity and position with respect to the inertial coordinate system of any point on the body. When the instantaneous positions and velocities of the strut attachment points and the feet are known, it is a straightforward, easily programed process to compute the shock absorber forces and torques acting on the body.

NUMERICAL INTEGRATION

Utilizing an IBM 7094 digital computer we solve these equations for time histories of vehicle tumbling motions by the very simplest kind of numerical integration based on equations of the following type

$$\dot{X}(t + \Delta t) = \dot{X}(t) + \Delta t \ddot{X}(t)$$

$$X(t + \Delta t) = X(t) + \Delta t \dot{X}(t)$$

This integration is very simple to program, and every check we have been able to make indicates that we get satisfactory accuracy with reasonable smallness of the integration time interval Δt. We are able to follow the motions of a vehicle from impact to rest or to overturning in a computer time of about half a minute to a minute.

RESULTS FOR A REALISTIC VEHICLE

Figure 5 is a photograph of a 1/6-scale model of a lunar-landing vehicle. Landing tests of this model are now in progress as a part of our experimental program. It is not clear from the photograph, but there are four symmetrically placed legs.

In the way of an example of what we are trying to do it will be interesting to compare some theoretical and experimental time histories of vehicle accelerations and shock absorber stroke loads. The experimental results come from impacts under earth gravity. All results, however, both experimental and theoretical, have been scaled to correspond to a full-scale version of this model landing under lunar gravity. Using full-scale values, not model values, the earth weight of the vehicle is approximately 11,500 pounds, the height of the center of gravity above the base plane is 13.5 feet, and the distance from the center of the base plane out to a foot is 13.2 feet. As can be seen, the legs are inverted tripods. The shock absorbers mounted in each strut are crushable aluminum honeycomb inserts which resist shortening of a strut. The honeycomb provides essentially constant stroke loads with full-scale values of 9,360 pounds in the upper struts and 4,680 pounds in the lower struts.

Figure 6 illustrates the type of landing which will be considered. In the rapidly expanding lunar-landing jargon, this would be described as a 2-2 downhill impact with no horizontal velocity. The vehicle drops straight down onto a sloping surface, striking on two feet simultaneously. It then rotates downhill to strike on the other two feet. The results which will be shown are for an impact at 10-feet-per-second sink velocity on a 10° slope. For these conditions the uphill feet lift off upon impact of the downhill feet, but the vehicle does not overturn and eventually falls back on the uphill feet.

In the analysis the coefficients of friction associated with the landing surface planes were set at very high values so that the feet were effectively stopped instantaneously upon contact with the landing surface. In the experiment spiked feet were mounted on the vehicle, and the landing surface was plywood bolted to concrete. The feet are brought to a sudden stop when they stick in the plywood. However, the surface is not altogether satisfactory for checking a theory in which the feet are assumed to stop instantaneously. Preliminary tests in which a single strut was impacted on plywood showed that by no means all of the kinetic energy at impact is expended in crushing the honeycomb shock absorbers. A substantial portion of the energy loss is involved in penetration of the plywood by the spiked feet. On the basis of the single-strut tests, when we landed the model on plywood we expected and got reductions on the order of 40 percent in the strokes of some of the shock absorbers due to the energy absorbed by the plywood, whereas in the theory all energy absorption is by shock absorber stroking.

In view of this situation, some of the correlations were surprisingly good as shown by figures 7 and 8. The solid curve in figure 7 is a plot against time of the component of acceleration along the longitudinal axis of the vehicle measured by an accelerometer mounted at the center of gravity. This is the acceleration the pilot would feel in the seat of his pants. The dotted line is the computed plot of this acceleration. Note that the acceleration is measured in earth g's. The first acceleration peak is produced by the initial impact of the uphill feet and the second one by the subsequent impact of the downhill feet. The period of relatively low acceleration in between the peaks is associated with the downhill rotation of the vehicle essentially as a rigid body. The time origin for the theory was chosen as the instant the uphill feet touched the surface. For the experiment the time origin was taken as the instant crushing of the honeycomb started in one of the upper struts of the uphill legs. The acceleration levels are a little over 2g, which is quite tolerable. The stepping down of the acceleration from its first peak value indicated by the theory comes about because theoretically the rear leg struts unload one by one, not simultaneously, the lower struts ceasing to crush prior to the upper strut. There is an indication of a similar stepping down in the measured accelerations, and as will be seen, at least one of the lower rear leg struts did unload before the upper strut.

The theory predicts quite well the durations of the acceleration pulses and also the time elapsed between impacts of the uphill and the downhill feet. In fact, the correlation is so good as to be a little perplexing since it was expected that there would be an effect associated with the interaction of the feet with the plywood, and since there was, as expected, substantially less stroking of the shock absorbers than predicted by the theory. The fact that peak accelerations were predicted, however, was very encouraging since it indicated that the shock absorption system was functioning as intended in its capacity as a load limiting device.

The curves in figure 8 show the axial load in the upper strut and the lower outboard strut of one of the uphill legs, measured by strain gages mounted in the struts. The horizontal lines indicate the theoretical loads up to the time the struts unload. Theoretically, both struts begin stroking the instant the foot touches the surface, and the lower strut unloads before the upper strut does. In the test results the lower strut loaded later and unloaded earlier than the upper strut. It is interesting that the duration of stroking was the same experimentally and theoretically although as previously noted the total strokes obtained experimentally were less than those predicted theoretically. Evidently the effect of the foot penetrating the plywood was to reduce the rate of stroking but not the time of stroking, and, since the stroke load does not depend on rate of crushing, the force pulses on the vehicle were substantially the same in the experiment and the calculation.

CONCLUDING REMARKS

The material presented represents progress to date in an attempt to establish through coordinated tests and analyses, an analytical model which can be relied upon to predict the landing characteristics of a lunar-landing vehicle. Very limited comparisons of experiment and theory indicate that equations of motion of an idealized vehicle, quite straightforward in its conception, will yield accurate predictions of the accelerations which will be felt by the pilots during the landing impact. It remains to be seen if the same equations will serve to predict other important features of the dynamical history of an impact. Of particular importance is the question of whether or not the equations adequately describe the stability of the vehicle against overturning.

REFERENCE

1. Walton, W. C., Jr.; Herr, R. W.; and Leonard, H. W.: Studies of Touchdown Stability for Lunar Landing Vehicles. Jour. of Spacecraft and Rockets, vol. 1, no. 5, pp. 552-556.

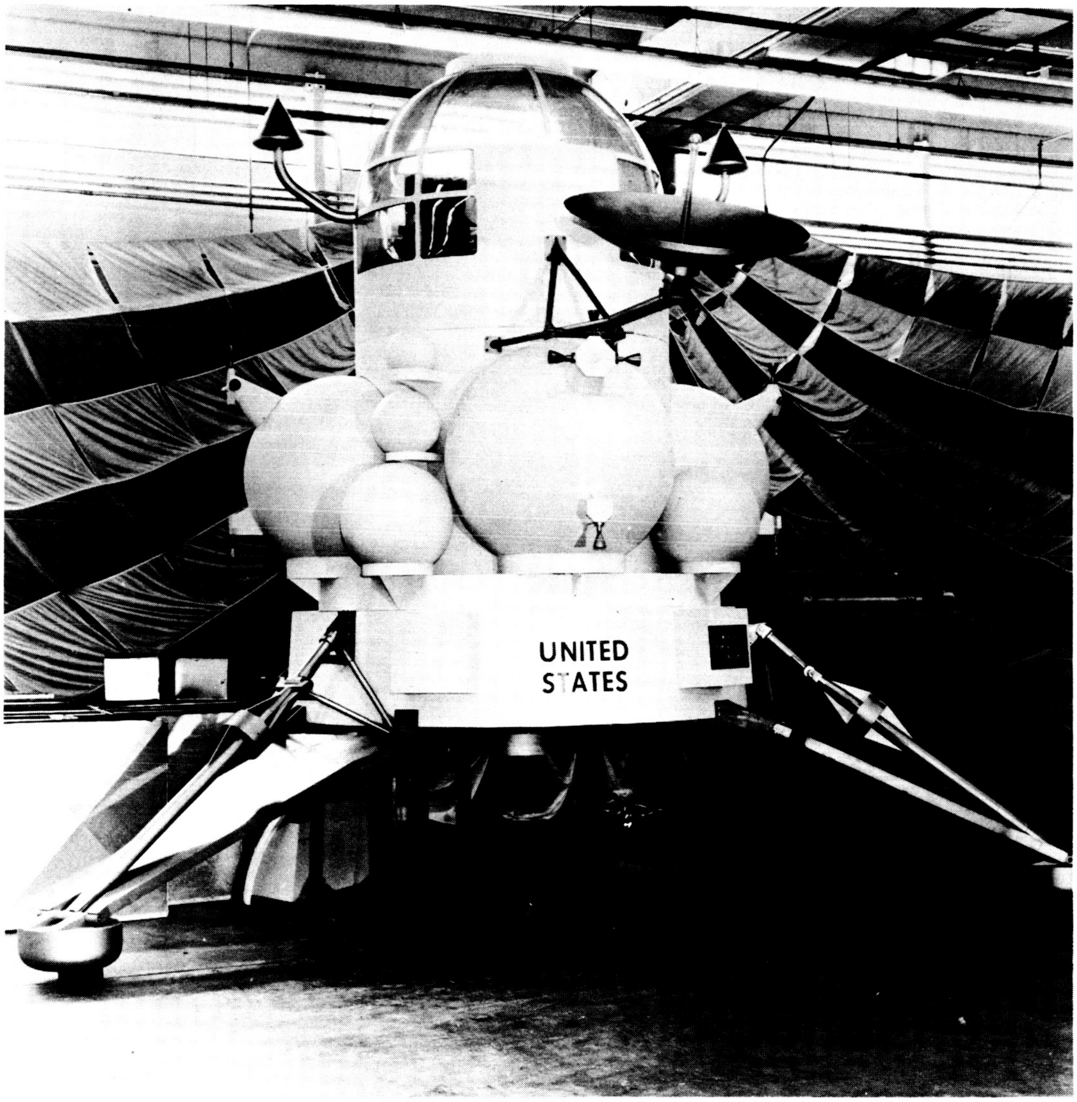

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Figure 1.- Lunar Excursion Module concept.

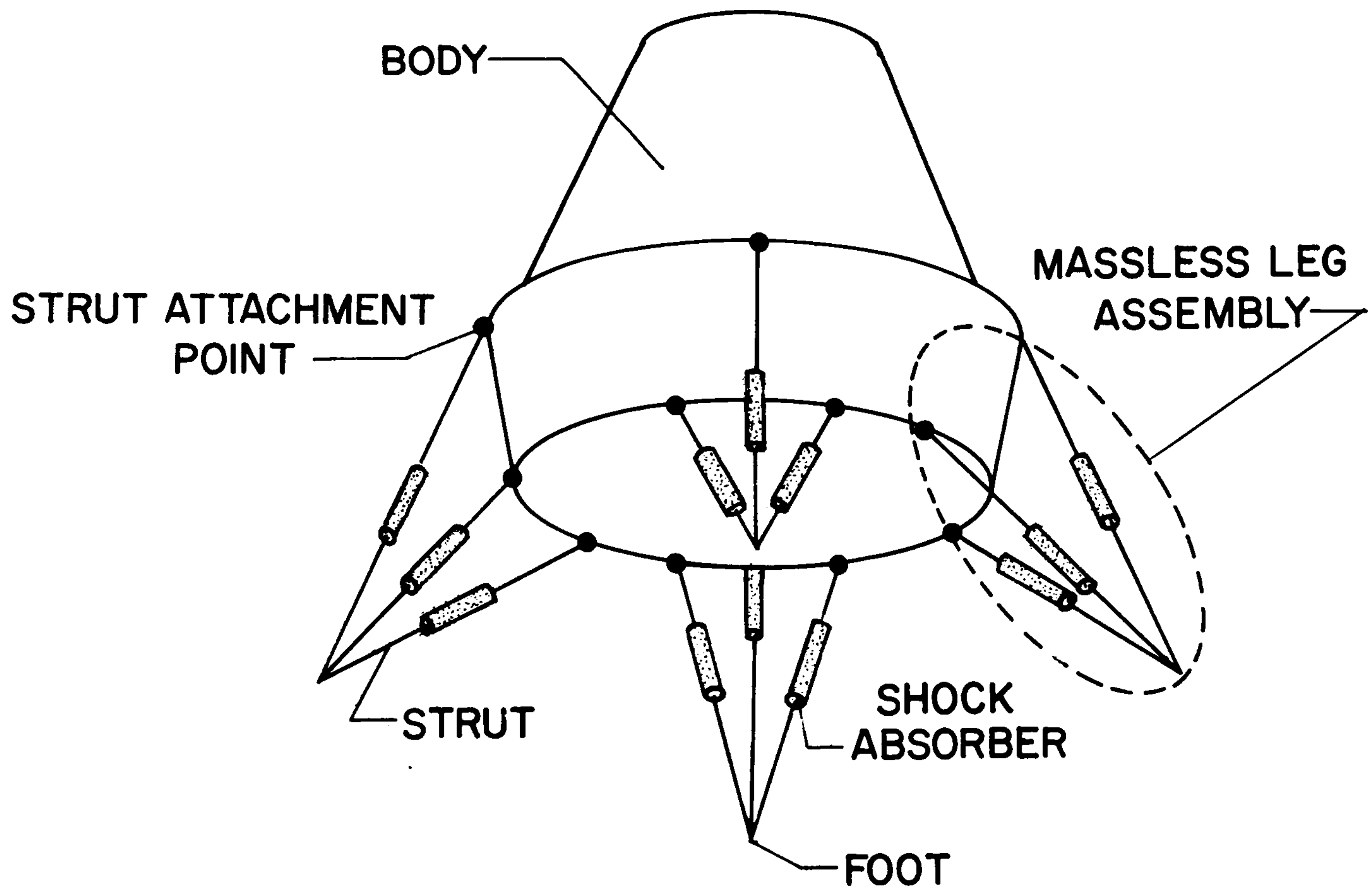

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Figure 2.- Analytical model.

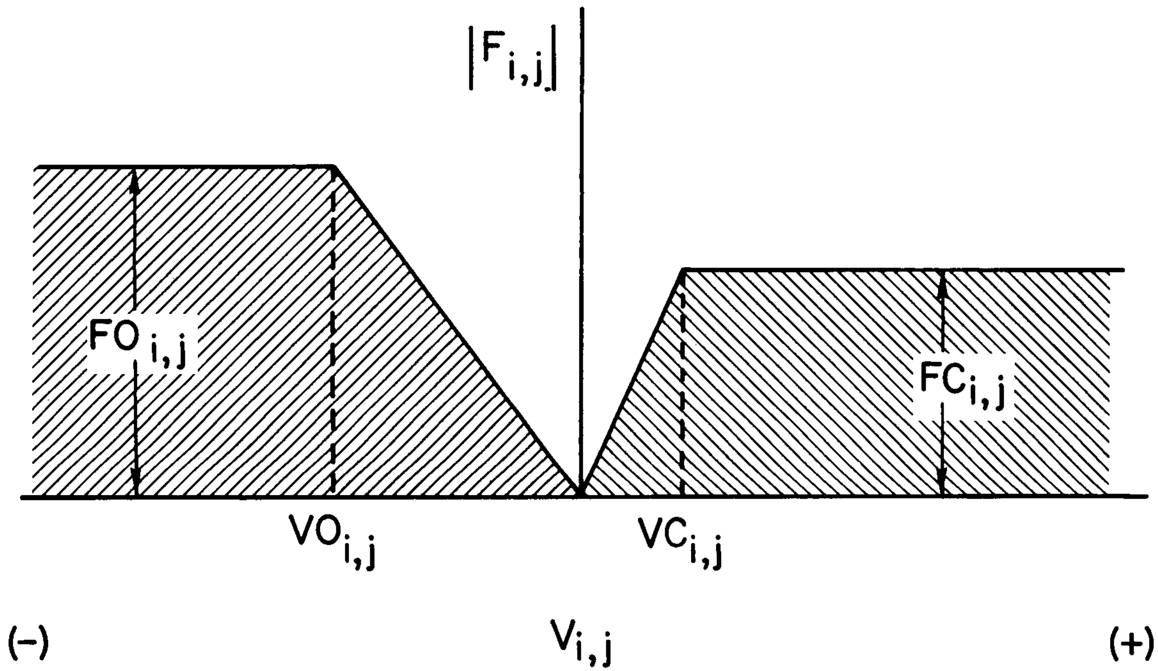

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Figure 3.- Schematic representation of shock absorber force.

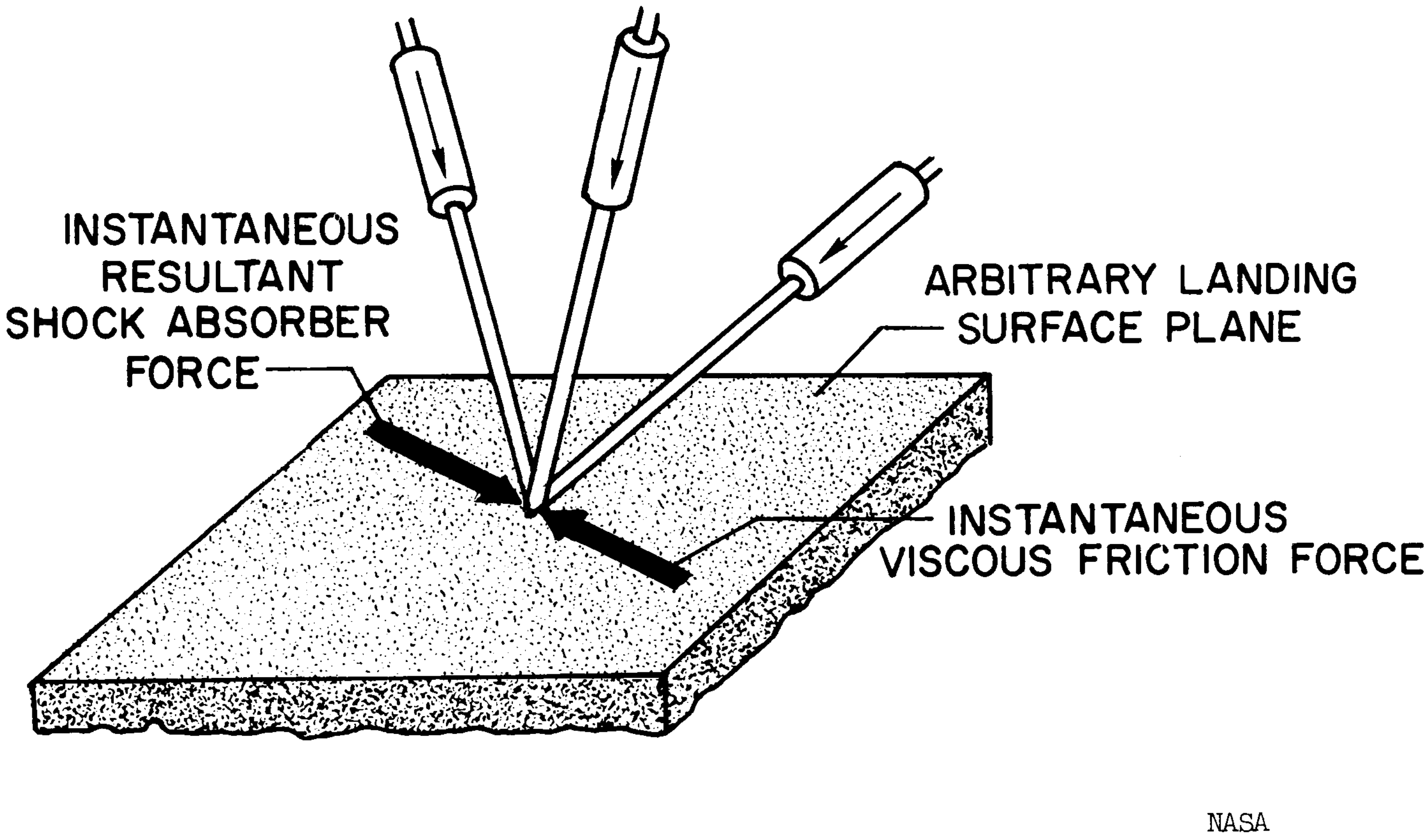

Figure 4.- Foot-ground interaction.

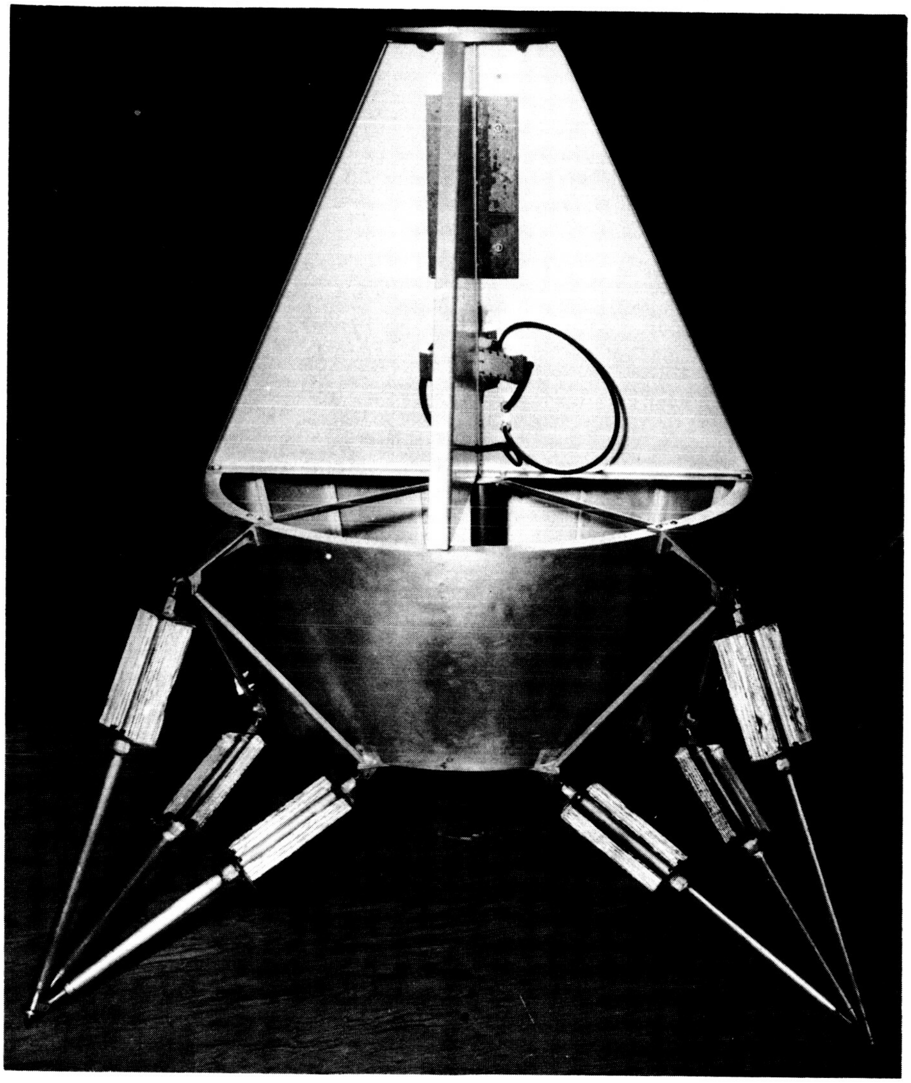

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Figure 5.- Langley 1/6-scale model.

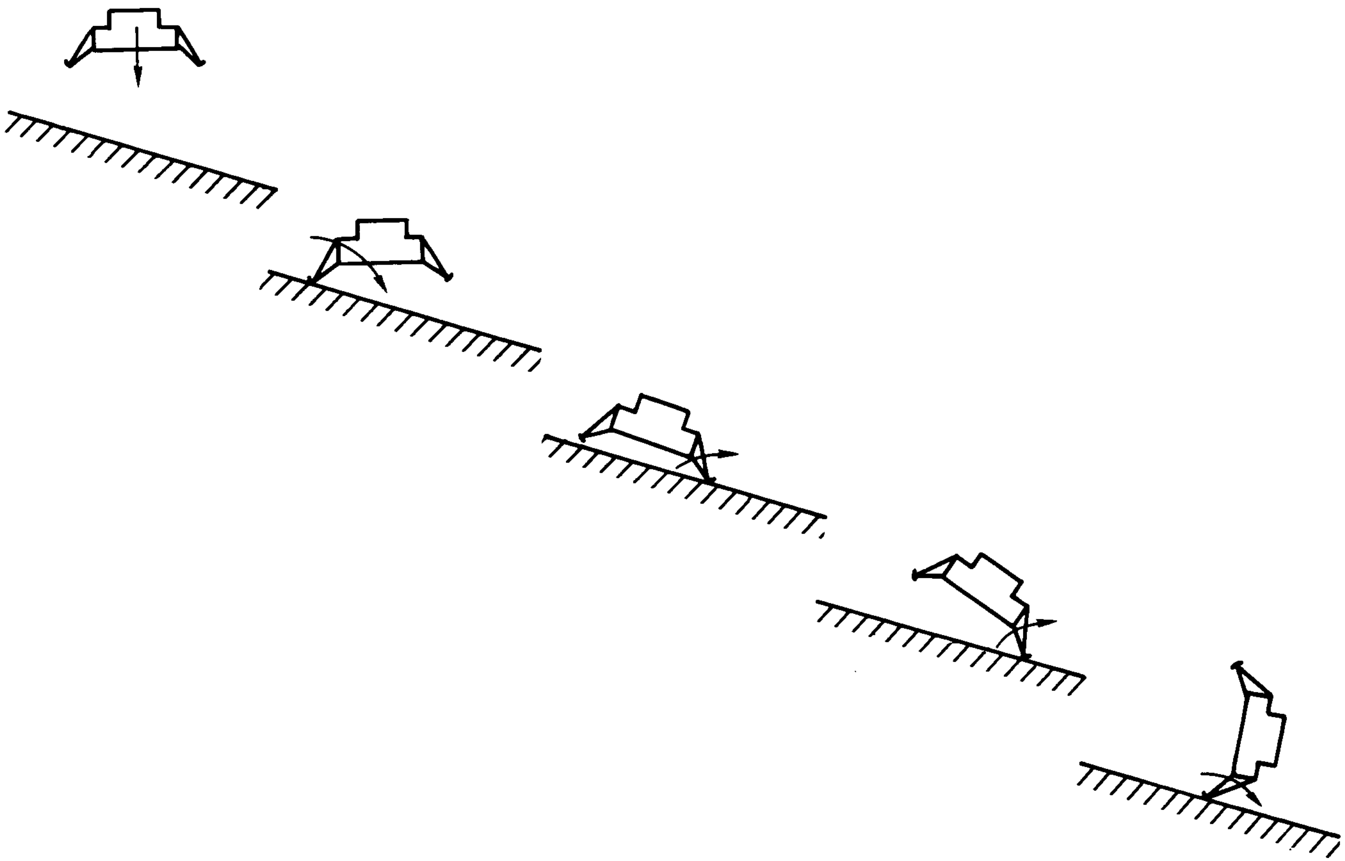

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Figure 6.- 2-2 and over landing.

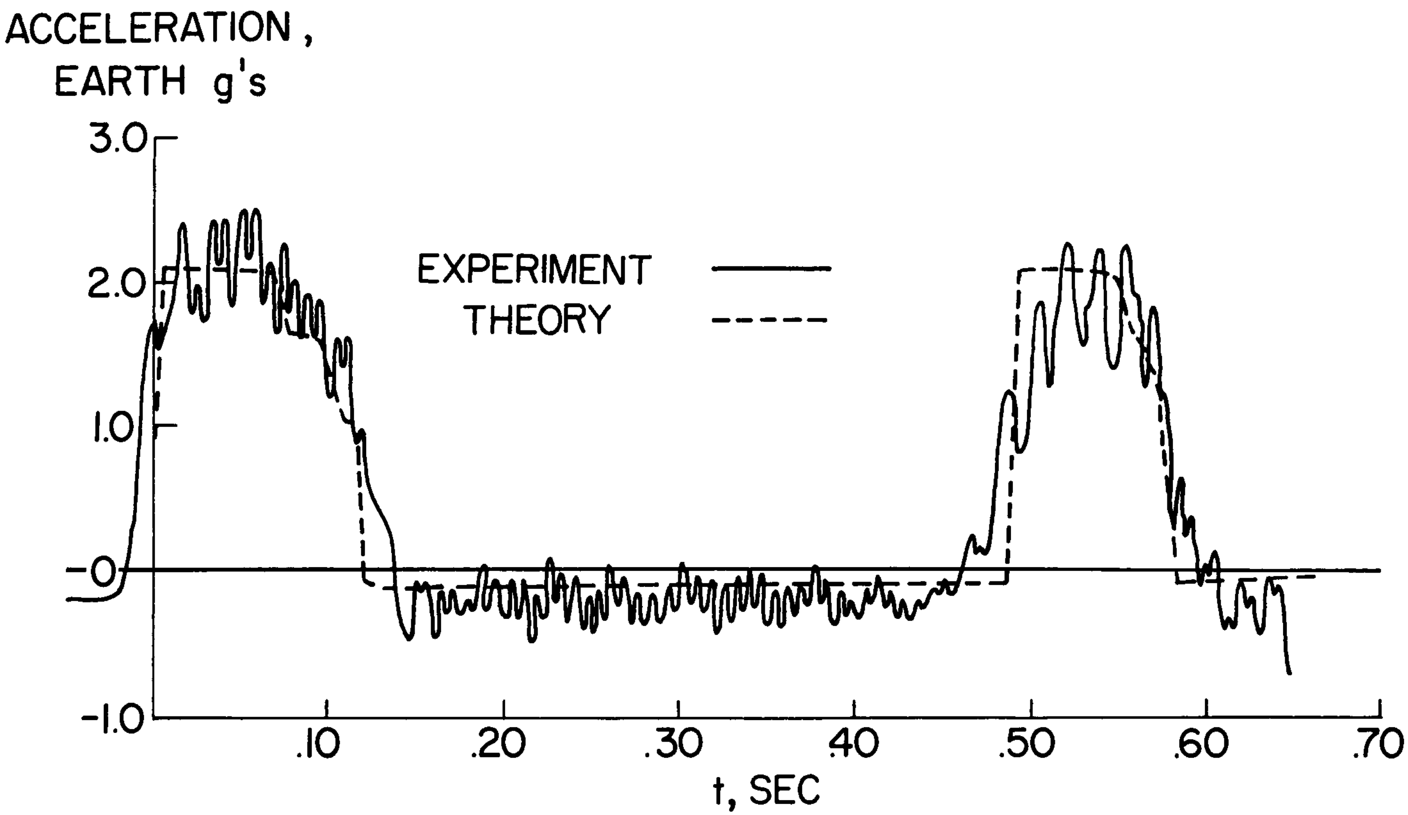

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Figure 7.- Longitudinal acceleration during 2-2 vertical landing (site slope = 10°; sink velocity = 10 fps).

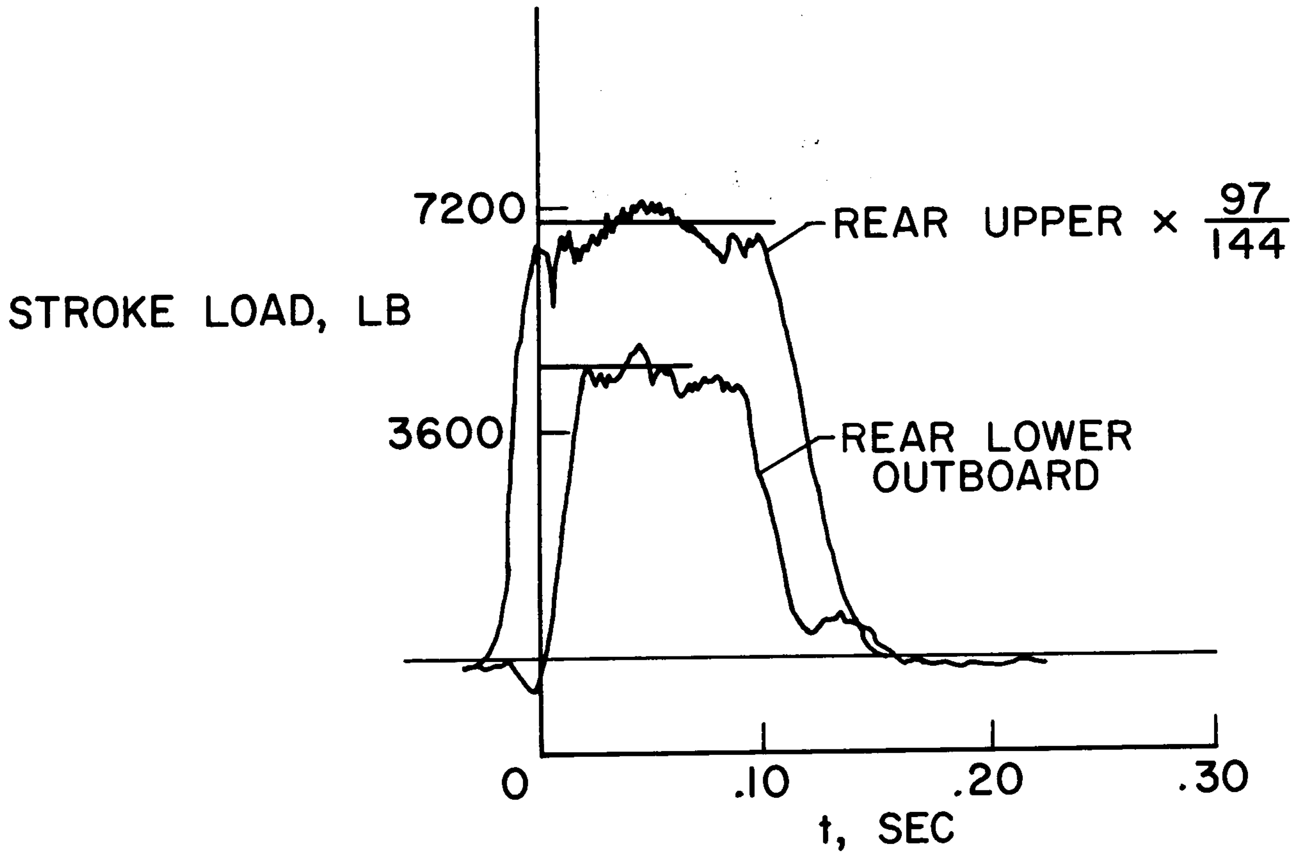

Figure 8.- Rear leg stroke loads during 2-2 vertical landing (site slope = 10°; sink velocity = 10 fps).

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